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published in
Review of Economics and Statistics
2019

DOI (link to publisher)
10.1162/rest_a_00762

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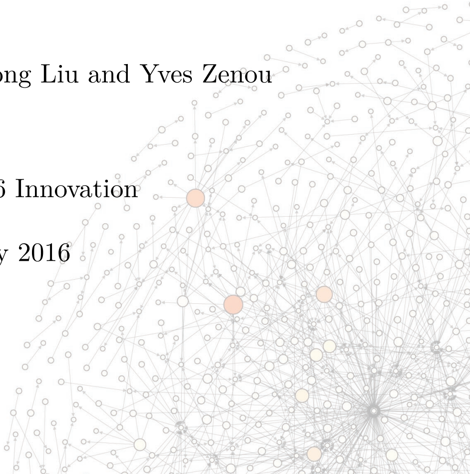
NBER SI 2016 Innovation

19th July 2016



Motivation

- R&D partnerships have become a widespread phenomenon characterizing technological dynamics, especially in industries with rapid technological development.[1]
- Firms have become more specialized on specific domains of a technology and they tend to combine their knowledge with the knowledge of other firms that are specialized in different technological domains.[2]
- Despite the importance of R&D collaborations for technological change and economic growth, there is no comprehensive study of R&D policy (network design, subsidies) in such networked markets.

[1] John Hagedoorn. "Inter-firm R&D partnerships: an overview of major trends and patterns since 1960". *Research Policy* 31.4 (2002), pp. 477–492.

[2] Martin L. Weitzman. "Recombinant Growth". *The Quarterly Journal of Economics* 113.2 (1998), pp. 331–360.

Contribution

- We study a structural model of R&D alliance networks where firms jointly form R&D collaborations to lower their production costs while competing on the product market.
- We provide a complete Nash equilibrium characterization, derive an efficiency analysis and determine the optimal R&D subsidy program that maximizes welfare.
- We then structurally estimate our model using a unique panel of R&D collaborations and annual company reports.
- We use our estimates to analyze the impact of R&D subsidy programs, and study how temporal changes in the network affect the optimal R&D policy.

The Model

- Firms can reduce their costs for production by investing into R&D as well as by establishing an R&D collaboration with another firm.
- The amount of this cost reduction depends on the effort e_i that a firm i and the effort e_j that its R&D collaboration partners $j \in \mathcal{N}_i$ invest into the collaboration.
- Given the effort level $e_i \in \mathbb{R}_+$, marginal cost c_i of firm i is given by

$$c_i = \bar{c}_i - e_i - \varphi \sum_{j=1}^{n} a_{ij} e_j, \tag{1}$$

  where $a_{ij} = 1$ if firms i and j set up a collaboration (0 otherwise) and $a_{ii} = 0$.
- The inverse demand function for firm i is

$$p_i = \bar{\alpha}_i - q_i - \rho \sum_{\substack{j \in \mathcal{M}_m, \\ j \neq i}} q_j, \tag{2}$$

- We assume that R&D effort is costly. In particular, the cost of R&D effort is an increasing function and given by $Z = \frac{1}{2}e_i^2$.[3] Firm i's profit π_i is then given by

$$\pi_i = (p_i - c_i)q_i - \frac{1}{2}e_i^2. \tag{3}$$

- Inserting marginal cost from Equation (1) and inverse demand from Equation (2) into Equation (3) gives

$$\pi_i = (\bar{\alpha}_i - \bar{c}_i)q_i - q_i^2 - \rho\sum_{j=1}^{n} b_{ij}q_iq_j + q_ie_i + \varphi q_i\sum_{j=1}^{n} a_{ij}e_j - \frac{1}{2}e_i^2, \tag{4}$$

where $b_{ij} \in \{0,1\}$ is the ij-th element of the matrix $\mathbf{B}$ indicating whether firms i and j operate in the same market.

[3] C. D'Aspremont and A. Jacquemin. "Cooperative and noncooperative R&D in duopoly with spillovers". *The American Economic Review* 78.5 (1988), pp. 1133–1137.

Equilibrium Characterization

- From the FOC with respect to R&D effort, $\frac{\partial \pi_i}{\partial e_i} = q_i - e_i = 0$, we find that $e_i = q_i$.[4]
- From the FOC with respect to output, $\frac{\partial \pi_i}{\partial q_i} = 0$, we obtain

$$q_i = \mu_i - \rho \sum_{j=1}^{n} b_{ij} q_j + \varphi \sum_{j=1}^{n} a_{ij} q_j, \tag{5}$$

where

- $\rho \sum_{j=1}^{n} b_{ij} q_j$ is the *product rivalry* effect,
- $\varphi \sum_{j=1}^{n} a_{ij} q_j$ is technology (or knowledge) *spillover* effect,
- $\mu_i \equiv \bar{\alpha}_i - \bar{c}_i$ is the ex ante *heterogeneity* in terms of firms ($\bar{\alpha}_i$) and markets ($\bar{c}_i$).

[4] W.M. Cohen and S. Klepper. "A reprise of size and R&D". *The Economic Journal* 106.437 (1996), pp. 925–951.

- Let $\lambda_{\mathrm{PF}}(\mathbf{A})$ be the largest eigenvalue of $\mathbf{A}$ and denote by $\underline{\mu} = \min\{\mu_i \mid i \in \mathcal{N}\}$ and $\overline{\mu} = \max\{\mu_i \mid i \in \mathcal{N}\}$, with $\underline{\mu} < \overline{\mu}$.
- If

$$\rho + \varphi < \left(\max \left\{ \lambda_{\mathrm{PF}}(\mathbf{A}), \max_{m=1,\ldots,M} \{(|\mathcal{M}_m| - 1)\} \right\} \right)^{-1} \tag{6}$$

and

$$\rho \max_{m=1,\ldots,M} \{(|\mathcal{M}_m| - 1)\} < 1 - \varphi \lambda_{\mathrm{PF}}(\mathbf{A}), \tag{7}$$

hold, then there exists a unique interior *Nash equilibrium* with output levels given by

$$\mathbf{q} = (\mathbf{I}_n + \rho \mathbf{B} - \varphi \mathbf{A})^{-1} \boldsymbol{\mu}. \tag{8}$$

- Assume that there is only a single market and let $\phi \equiv \frac{\varphi}{1-\rho}$. Then there exists a unique interior Nash equilibrium with output levels given by

$$\mathbf{q} = \frac{1}{1-\rho}\left(\mathbf{b}_{\boldsymbol{\mu}}\left(G,\phi\right) - \frac{\rho\|\mathbf{b}_{\boldsymbol{\mu}}\left(G,\phi\right)\|_1}{1+\rho(\|\mathbf{b}_{\boldsymbol{u}}\left(G,\phi\right)\|_1 - 1)}\mathbf{b}_{\mathbf{u}}\left(G,\phi\right)\right), \quad (9)$$

where $\mathbf{b}_{\boldsymbol{\mu}}(G,\phi)$ is the $\boldsymbol{\mu}$-weighted *Katz-Bonacich centrality*[5] defined by

$$\mathbf{b}_{\boldsymbol{\mu}}\left(G,\phi\right) = \left(\mathbf{I}_n - \phi\mathbf{A}\right)^{-1}\boldsymbol{\mu} = \sum_{k=0}^{\infty}\phi^k\mathbf{A}^k\boldsymbol{\mu}.$$

- The coefficient $a_{ij}^{[k]}$ in the (i,j) element of $\mathbf{A}^k$ counts the number of walks of length k in G between i and j.

[5] Phillip Bonacich. "Power and Centrality: A Family of Measures". *American Journal of Sociology* 92.5 (1987), pp. 1170–1182.

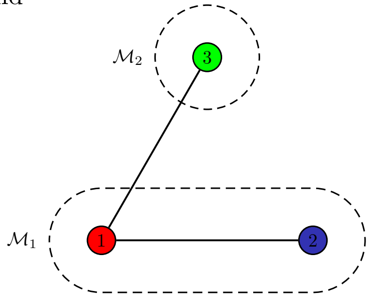
Example

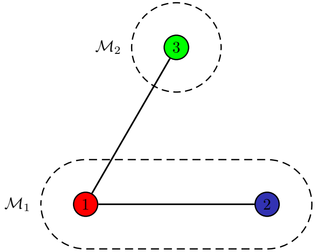
- Consider an industry composed of 3 firms and 2 sectors, $\mathcal{M}_1$ and $\mathcal{M}_2$, where firm 1 and 2, as well as firm 1 and firm 3 have an R&D collaboration, and firm 1 and 2 operate in the same market $\mathcal{M}_1$.

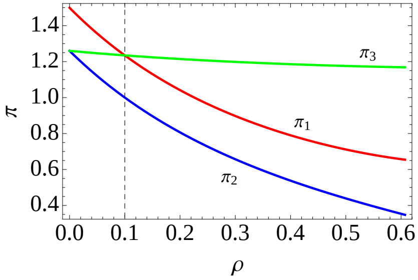
- Then the adjacency matrix $\mathbf{A}$ and the competition matrix $\mathbf{B}$ are given by

$$\mathbf{A} = \begin{pmatrix} 0 & 1 & 1 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix},$$

$$\mathbf{B} = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}.$$







- Firm 1 enjoys higher profits due to having the largest number of R&D collaborations when competition is weak (small ρ), but its profits are falling with increasing ρ, becoming smaller than the profits of firm 3 if $\rho > \varphi$.
- This result highlights the key trade off faced by firms between the *technology spillover effect* and the *product rivalry effect* (cf. Bloom et al. 2013).

The R&D Subsidy Program

- An active government is introduced that can provide a (potentially firm specific) subsidy, $s_i \geq 0$, per unit of R&D.
- The profit of firm i can then be written as (cf. e.g. Hinloopen, 2001, 2003; Spencer, 1983)[6]

$$\pi_i = \mu_i q_i - q_i^2 - \rho q_i \sum_{j \neq i} b_{ij} q_j + q_i e_i + \varphi q_i \sum_{j=1}^{n} a_{ij} e_j - \frac{1}{2} e_i^2 + s_i e_i. \quad (10)$$

- If we define net welfare as $\overline{W}(G, \mathbf{s}) \equiv W(G, \mathbf{s}) - \sum_{i=1}^{n} e_i s_i$, then the social planner's problem is given by

$$\mathbf{s}^* = \arg\max_{\mathbf{s} \in \mathbb{R}_+^n} \overline{W}(G, \mathbf{s}).$$

[6] J. Hinloopen. "Subsidizing R&D Cooperatives". *De Economist* 149.3 (2001), pp. 313–345; Barbara J. Spencer and James A. Brander. "International R & D Rivalry and Industrial Strategy". *The Review of Economic Studies* 50.4 (1983), pp. 707–722.

Optimal Subsidies

- The government (or the planner) is here introduced as an agent that can set subsidy rates on R&D effort (first stage) in a period before the firms spend on R&D (second stage).
- The unique interior Nash equilibrium with targeted subsidies (in the second stage) is given by $\mathbf{q} = \tilde{\mathbf{q}} + \mathbf{R}\mathbf{s}$, where $\mathbf{R} = \mathbf{M}\left(\mathbf{I}_n + \varphi \mathbf{A}\right)$, $\tilde{\mathbf{q}} = \mathbf{M}\boldsymbol{\mu}$, equilibrium efforts are given by $e_i = q_i + s_i$ and profits are given by $\pi_i = (q_i^2 + s_i^2)/2$.
- Further, if the matrix $\mathbf{H} \equiv \mathbf{I}_n + 2\left(\mathbf{I}_n - \mathbf{R}^\top \left(\mathbf{I}_n + \frac{\rho}{2}\mathbf{B}\right)\right)\mathbf{R}$ is positive definite, the optimal subsidy levels (in the first stage) are given by

$$\mathbf{s}^* = 2\left(\mathbf{H} + \mathbf{H}^\top\right)^{-1}\left(2\mathbf{R}^\top\left(\mathbf{I}_n + \frac{\rho}{2}\mathbf{B}\right) - \mathbf{I}_n\right)\tilde{\mathbf{q}}.$$

Empirical Implications – Data

- For the purpose of estimating our model we use the combined Thomson SDC and MERIT-CATI databases.[7]
- This database contains information about strategic technology agreements, including any alliance that involves some arrangements for mutual transfer of technology or joint research, such as joint research pacts, joint development agreements, cross licensing, R&D contracts, joint ventures and research corporations.
- We use annual data about balance sheets and income statements from Standard & Poor's Compustat U.S. fundamentals database, and Burea Van Dijk's Osiris database.

[7] M.A. Schilling. "Understanding the alliance data". *Strategic Management Journal* 30.3 (2009), pp. 233–260. ISSN: 1097-0266.

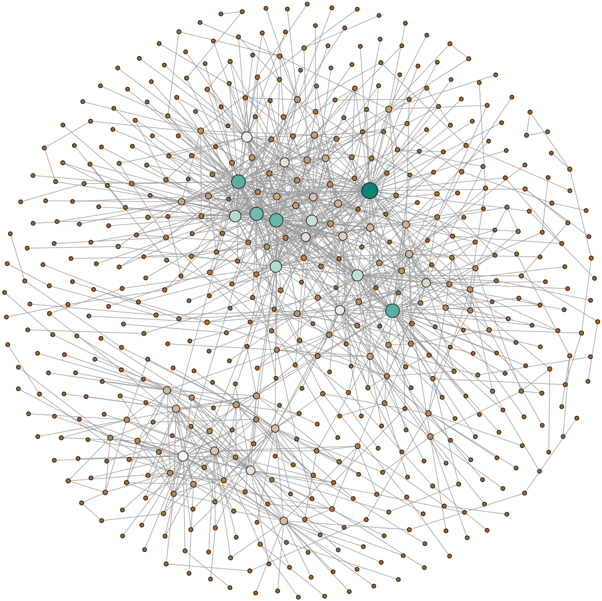


Figure: The largest connected component of the R&D collaboration network with all links accumulated until the year 2005.

Empirical Implications - Estimation

- Our empirical counterpart of the marginal cost c_{it} of firm i from Equation (1) at period t has a fixed cost equal to $\bar{c}_{it} = \eta_i^* - \epsilon_{it} - x_{it}\beta$, so that

$$c_{it} = \eta_i^* - \varepsilon_{it} - \beta x_{it} - e_{it} - \varphi \sum_{j=1}^{n} a_{ij,t} e_{jt}, \tag{11}$$

  - x_{it} is a measure for the productivity of firm i,
  - η_i^* captures the unobserved (to the econometrician) time-invariant characteristics of the firms, and
  - ε_{it} (i.i.d.) captures the remaining unobserved (to the econometrician) characteristics of the firms.
- Denote by $\kappa_t \equiv \bar{\alpha}_t$ and $\eta_i \equiv \bar{\alpha}_m - \eta_i^*$, where κ_t captures a *time fixed effect* due to exogenous demand shifters while η_i, which includes both $\bar{\alpha}_m$ and η_i^*, captures a *firm fixed effect*.

- The econometric equivalent to the best response output level is

$$q_{it} = \varphi \sum_{j=1}^{n} a_{ij,t} q_{jt} - \rho \sum_{j=1}^{n} b_{ij} q_{jt} + \beta x_{it} + \eta_i + \kappa_t + \epsilon_{it}, \tag{12}$$

  with an i.i.d. error term ϵ_{it}.
- Output q_{it} is calculated using sales divided by country-year-industry price deflators from the OECD-STAN database.
- The exogenous variable x_{it} is the firm's time-lagged R&D stock using a perpetual inventory method with a 15% depreciation rate,[8] with R&D tax credits as instruments.
- Equation (12) corresponds to a high-order *Spatial Auto-Regressive (SAR)* model with two spatial lags $\mathbf{A}_t\mathbf{q}_t$ and $\mathbf{B}\mathbf{q}_t$.[9]

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[8] Bronwyn H Hall, Adam B Jaffe, and Manuel Trajtenberg. "Market value and patent citations: A first look". *National Bureau of Economic Research, Working Paper No. w7741* (2000).

[9] L. Lee and X. Liu. "Efficient GMM estimation of high order spatial autoregressive models with autoregressive disturbances". *Econometric Theory* 26.1 (2010), pp. 187–230.

- Output q_{it} is calculated using sales divided by country-year-industry price deflators from the OECD-STAN database.[10]
- The network data stems from the combined CATI-SDC databases and we set $a_{ij,t} = 1$ if there exists an R&D collaboration between firms i and j in the last s years before time t, where s is the duration of an alliance.
- The exogenous variable x_{it} is the firm's time-lagged R&D stock at the time $t-1$.
- Finally, we measure b_{ij} as in the theoretical model so that $b_{ij} = 1$ if firms i and j are the same industry (measured by the industry SIC codes at the 4-digit level) and zero otherwise.

[10] Peter N. Gal. "Measuring total factor productivity at the firm level using OECD-ORBIS". *OECD Working Paper, ECO/WKP(2013)41* (2013).

Simultaneity of Product Quantities

- We use instrumental variables when estimating our outcome Equation (12) to deal with the issue of *simultaneity* of q_{it} and q_{jt}.
- We *instrument* $\sum_{j=1}^{n} a_{ij,t} q_{jt}$ by the *time-lagged total R&D stock* of all firms with an R&D collaboration with firm i, i.e. $\sum_{j=1}^{n} a_{ij,t} x_{jt}$, and instrument $\sum_{j=1}^{n} b_{ij} q_{jt}$ by the time-lagged total R&D stock of all firms that operate in the same industry as firm i, i.e. $\sum_{j=1}^{n} b_{ij} x_{jt}$.
- To allow for potential correlation in unobservables across firms (e.g. from unobserved R&D subsidies), the standard deviation of the IV estimator is estimated by the *spatial heteroskedasticity and autocorrelation consistent (HAC)* estimator.[11]

[11] Harry H. Kelejian and Ingmar R. Prucha. "HAC estimation in a spatial framework". *Journal of Econometrics* 140.1 (2007), pp. 131–154.

Endogeneity of the R&D Stock

- To deal with the potential endogeneity of the time-lagged R&D stock, we use supply side shocks from tax-induced changes to the user cost of R&D to construct *instrumental variables for R&D expenditures* as in Bloom et al. (2013).[12]
- Let w_{it} denote the time-lagged R&D tax credit firm i received at time $t-1$.
- We then instrument $\bar{q}_{a,it}$ by the time-lagged total R&D tax credits of all firms with an R&D collaboration with firm i, i.e. $\sum_{j=1}^{n} a_{ij,t} w_{jt}$, instrument $\bar{q}_{b,it}$ by the time-lagged total R&D tax credits of all firms that operate in the same industry as firm i, i.e. $\sum_{j=1}^{n} b_{ij} w_{jt}$, and instrument the time-lagged R&D stock x_{it} by the time-lagged R&D tax credit w_{it}.

[12] Nicholas Bloom, Mark Schankerman, and John Van Reenen. "Identifying technology spillovers and product market rivalry". *Econometrica* 81.4 (2013), pp. 1347–1393.

Endogenous Network Formation

- $\mathbf{A}_t$ is endogenous if there exists an *unobservable factor* that affects both the output, q_{it} and the R&D alliance, $a_{ij,t}$.
- If the unobservable factor is firm-specific, then it is captured by the firm fixed-effect η_i.
- If the unobservable factor is time-specific, then it is captured by the time fixed-effect κ_t.
- However, it may still be that there are some unobservable firm-specific factors that do vary over time and that affect the propensity of R&D *collaborations* and thus make the matrix $\mathbf{A}_t = [a_{ij,t}]$ *endogeneous*.

- We consider IVs based on the predicted R&D alliance matrix, i.e. $\widehat{\mathbf{A}}_t \mathbf{X}_t$.
- We obtain the predicted link-formation probability $\hat{a}_{ij,t}$ from the *logistic regression* of $a_{ij,t}$ on:
    - whether firms i and j *collaborated before* time $t-s$, where s is the duration of an alliance,
    - whether firms i and j shared a *common collaborator before* time $t-s$,
    - the time-lagged *technological proximity*[13] of firms i and j represented by $P_{ij,t-s}$ and $P^2_{ij,t-s}$,
    - whether firms i and j are are in the *same market*, and
    - whether firms i and j are located in the *same city*.

[13] Adam B. Jaffe. "Technological Opportunity and Spillovers of R & D: Evidence from Firms' Patents, Profits, and Market Value". *The American Economic Review* 76.5 (1986), pp. 984–1001; Nicholas Bloom, Mark Schankerman, and John Van Reenen. "Identifying technology spillovers and product market rivalry". *Econometrica* 81.4 (2013), pp. 1347–1393.

We then use the following step-wise procedure to estimate our model:[14]

- **Step 1:** Estimate a logistic link formation model. Use the estimated model to predict links. Denote the predicted adjacency matrix by $\widehat{\mathbf{A}}_t$ and its elements by $\widehat{a}_{ij,t}$.
- **Step 2:** Estimate the outcome Equation (12) using $\sum_{j=1}^{n} \widehat{a}_{ij,t}x_{jt}$ and $\sum_{j=1}^{n} b_{ij}x_{jt}$ as IVs for $\sum_{j=1}^{n} a_{ij,t}q_{jt}$ and $\sum_{j=1}^{n} b_{ij,t}q_{jt}$, respectively.

[14] Bryan S. Graham. "Methods of Identification in Social Networks". *Annual Review of Economics* 7.1 (2015), pp. 465–485.

Estimation Results

Table: (**Step 2**) Parameter estimates from a panel regression of Equation (12) with IVs based on time-lagged tax credits. Model A includes only time fixed effects, while Model B includes both firm and time fixed effects. The dependent variable is output obtained from deflated sales. The estimation is based on the observed alliances in the years 1967–2006.

	Model A		Model B	
φ	-0.0133	(0.0114)	0.0128*	(0.0069)
ρ	0.0182***	(0.0018)	0.0156**	(0.0076)
β	0.0054***	(0.0004)	0.0023***	(0.0006)
# firms	1186		1186	
# observations	16924		16924	
Wald F	138.311		78.791	
firm fixed effects	no		yes	
time fixed effects	yes		yes	

*** Statistically significant at 1% level.
** Statistically significant at 5% level.
* Statistically significant at 10% level.

Table: (**Step 1**) Link formation regression results. Technological similarity, f_{ij}, is measured using either the Jaffe or the Mahalanobis patent similarity measures. The dependent variable $a_{ij,t}$ indicates if an R&D alliance exists between firms i and j at time t. The estimation is based on the observed alliances in the years 1967–2006.

technological similarity	Jaffe	Mahalanobis
Past collaboration	0.5980***	0.5922***
	(0.0150)	(0.0149)
Past common collaborator	0.1161***	0.1166***
	(0.0238)	(0.0236)
$f_{ij,t-s-1}$	13.6120***	6.0518***
	(0.6896)	(0.3322)
$f^2_{ij,t-s-1}$	-20.1916***	-3.8699***
	(1.7420)	(0.4623)
$city_{ij}$	1.1299***	1.1403***
	(0.1017)	(0.1017)
$market_{ij}$	0.8450***	0.8559***
	(0.0424)	(0.0422)
# observations	3,964,120	3,964,120
McFadden's R^2	0.0812	0.0813

*** Statistically significant at 1% level.
** Statistically significant at 5% level.
* Statistically significant at 10% level.

R&D Subsidies – Welfare Impact

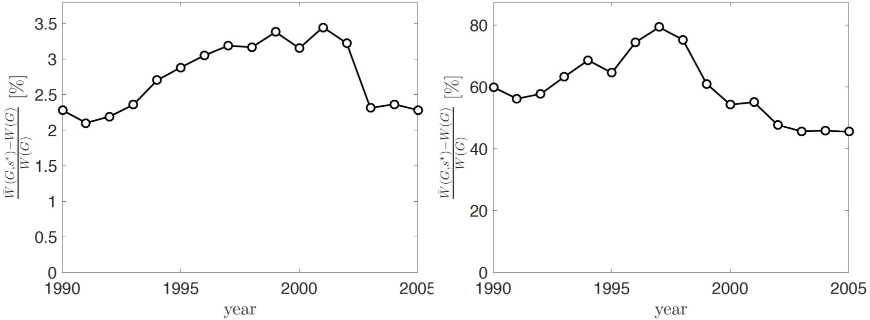

Figure: (Left panel) The percentage increase in welfare due to a homogeneous subsidy, s^*, over time. (Right panel) The percentage increase in welfare due to (firm specific) targeted subsidies, $\mathbf{s}^*$, over time.

R&D Subsidies Rankings

Table: Subsidies ranking for the year 1990 for the first 25 firms.

Firm	Share [%][a]	num pat.	$\mathbf{d}$	$\mathbf{v}_{\mathrm{PF}}$	Betweenness[b]	Closeness[c]	$\mathbf{q}$ [%]	hom. sub. [%][d]	tar. sub. [%][e]	SIC[f]	Rank
General Motors Corp.	9.2732	76644	88	0.1009	0.0007	0.0493	6.9866	0.0272	0.3027	3711	1
Exxon Corp.	7.7132	21954	22	0.0221	0.0000	0.0365	5.4062	0.0231	0.1731	2911	2
Ford Motor Co.	7.3456	20378	6	0.0003	0.0000	0.0153	3.7301	0.0184	0.0757	3711	3
AT&T Corp.	9.5360	5692	8	0.0024	0.0000	0.0202	3.2272	0.0156	0.0565	4813	4
Chevron	2.8221	12789	23	0.0226	0.0001	0.0369	2.5224	0.0098	0.0418	2911	5
Texaco	2.9896	9134	22	0.0214	0.0000	0.0365	2.4965	0.0095	0.0415	2911	6
Lockheed	42.3696	2	51	0.0891	0.0002	0.0443	1.5639	0.0035	0.0196	3760	7
Mobil Corp.	4.2265	3	0	0.0000	0.0000	0.0000	1.9460	0.0111	0.0191	2911	8
TRW Inc.	5.3686	9438	43	0.0583	0.0002	0.0415	1.4509	0.0027	0.0176	3714	9
Altria Group	43.6382	0	0	0.0000	0.0000	0.0000	1.4665	0.0073	0.0117	2111	10
Alcoa Inc.	11.4121	4546	36	0.0287	0.0002	0.0372	1.2136	0.0032	0.0114	3350	11
Shell Oil Co.	14.6777	9504	0	0.0000	0.0000	0.0000	1.4244	0.0073	0.0109	1311	12
Chrysler Corp.	2.2414	3712	6	0.0017	0.0000	0.0218	1.3935	0.0075	0.0109	3711	13
Schlumberger Ltd. Inc.	25.9218	9	18	0.0437	0.0000	0.0370	1.1208	0.0029	0.0099	1389	14
Hewlett-Packard Co.	7.1106	6606	64	0.1128	0.0002	0.0417	1.1958	0.0047	0.0093	3570	15
Intel Corp.	9.3900	1132	67	0.1260	0.0003	0.0468	1.0152	0.0018	0.0089	3674	16
Hoechst Celanese Corp.	5.6401	516	38	0.0368	0.0002	0.0406	1.0047	0.0021	0.0085	2820	17
Motorola	14.1649	21454	70	0.1186	0.0004	0.0442	1.0274	0.0028	0.0080	3663	18
PPG Industries Inc.	13.3221	24904	20	0.0230	0.0000	0.0366	0.9588	0.0021	0.0077	2851	19
Himont Inc.	0.0000	59	28	0.0173	0.0001	0.0359	0.8827	0.0014	0.0072	2821	20
GTE Corp.	3.1301	4	0	0.0000	0.0000	0.0000	1.1696	0.0067	0.0070	4813	21
National Semiconductor Corp.	4.0752	1642	43	0.0943	0.0001	0.0440	0.8654	0.0012	0.0068	3674	22
Marathon Oil Corp.	7.9828	202	0	0.0000	0.0000	0.0000	1.1306	0.0060	0.0068	1311	23
Bellsouth Corp.	2.4438	3	14	0.0194	0.0000	0.0329	1.0926	0.0060	0.0064	4813	24
Nynex	2.3143	26	24	0.0272	0.0001	0.0340	0.9469	0.0049	0.0052	4813	25

[a] Market share in the primary 4-digit SIC sector in which the firm is operating. In case of missing data the closest year with sales data available has been used.

[b] The normalized betweenness centrality is the fraction of all shortest paths in the network that contain a given node, divided by $(n-1)(n-2)$, the maximum number of such paths.

[c] The closeness centrality of node i is computed as $\frac{2}{n-1}\sum_{j=1}^{n} 2^{-\ell_{ij}(G)}$, where $\ell_{ij}(G)$ is the length of the shortest path between i and j in the network G (Dangalchev, 2006), and the factor $\frac{2}{n-1}$ is the maximal centrality attained for the center of a star network.

[d] The homogeneous subsidy for each firm i is computed as $e_i^* s^*$, relative to the average homogeneous subsidy $\frac{1}{n} s^* \sum_{j=1}^{n} e_j^*$.

[e] The targeted subsidy for each firm i is computed as $e_i^* s_i^*$, relative to the average targeted subsidy $\frac{1}{n}\sum_{j=1}^{n} e_j^* s_j^*$.

[f] The primary 4-digit SIC code of a firm in the database.

Table: Subsidies ranking for the year 2005 for the first 25 firms.

Firm	Share [%][a]	num pat.	$\mathbf{d}$	$\mathbf{v}_{\mathrm{PF}}$	Betweenness[b]	Closeness[c]	$\mathbf{q}$ [%]	hom. sub. [%][d]	tar. sub. [%][e]	SIC[f]	Rank
General Motors Corp.	3.9590	90652	19	0.0067	0.0002	0.0193	4.1128	0.0174	0.2186	3711	1
Ford Motor Co.	3.6818	27452	7	0.0015	0.0000	0.0139	3.4842	0.0153	0.1531	3711	2
Exxon Corp.	4.0259	53215	6	0.0007	0.0001	0.0167	2.9690	0.0132	0.1108	2911	3
Microsoft Corp.	10.9732	10639	62	0.1814	0.0020	0.0386	1.6959	0.0057	0.0421	7372	4
Pfizer Inc.	3.6714	74253	65	0.0298	0.0034	0.0395	1.6796	0.0069	0.0351	2834	5
AT&T Corp.	0.0000	16284	0	0.0000	0.0000	0.0000	1.5740	0.0073	0.0311	4813	6
Motorola	6.6605	70583	66	0.1598	0.0017	0.0356	1.3960	0.0053	0.0282	3663	7
Intel Corp.	5.0169	28513	72	0.2410	0.0011	0.0359	1.3323	0.0050	0.0249	3674	8
Chevron	2.2683	15049	10	0.0017	0.0001	0.0153	1.3295	0.0058	0.0243	2911	9
Hewlett-Packard Co.	14.3777	38597	7	0.0288	0.0000	0.0233	1.1999	0.0055	0.0183	3570	10
Altria Group	20.4890	5	2	0.0000	0.0000	0.0041	1.1753	0.0054	0.0178	2111	11
Johnson & Johnson Inc.	3.6095	31931	40	0.0130	0.0015	0.0346	1.1995	0.0051	0.0173	2834	12
Texaco	0.0000	10729	0	0.0000	0.0000	0.0000	1.0271	0.0055	0.0124	2911	13
Shell Oil Co.	0.0000	12436	0	0.0000	0.0000	0.0000	0.9294	0.0045	0.0108	1311	14
Chrysler Corp.	0.0000	5112	0	0.0000	0.0000	0.0000	0.9352	0.0052	0.0101	3711	15
Bristol-Myers Squibb Co.	1.3746	16	35	0.0052	0.0009	0.0326	0.8022	0.0034	0.0077	2834	16
Merck & Co. Inc.	1.5754	52036	36	0.0023	0.0007	0.0279	0.8252	0.0038	0.0077	2834	17
Marathon Oil Corp.	5.5960	229	0	0.0000	0.0000	0.0000	0.7817	0.0039	0.0076	1311	18
GTE Corp.	0.0000	5	0	0.0000	0.0000	0.0000	0.7751	0.0041	0.0073	4813	19
Pepsico	36.6491	991	0	0.0000	0.0000	0.0000	0.7154	0.0035	0.0066	2080	20
Bellsouth Corp.	0.9081	2129	0	0.0000	0.0000	0.0000	0.7233	0.0039	0.0063	4813	21
Johnson Controls Inc.	22.0636	304	11	0.0027	0.0001	0.0159	0.6084	0.0021	0.0063	2531	22
Dell	18.9098	80	2	0.0190	0.0000	0.0216	0.6586	0.0028	0.0061	3571	23
Eastman Kodak Co	5.5952	109714	17	0.0442	0.0001	0.0262	0.6171	0.0023	0.0060	3861	24
Lockheed	48.9385	9817	44	0.0434	0.0003	0.0223	0.6000	0.0028	0.0049	3760	25

[a] Market share in the primary 4-digit SIC sector in which the firm is operating. In case of missing data the closest year with sales data available has been used.

[b] The normalized betweenness centrality is the fraction of all shortest paths in the network that contain a given node, divided by $(n-1)(n-2)$, the maximum number of such paths.

[c] The closeness centrality of node i is computed as $\frac{2}{n-1}\sum_{j=1}^{n} 2^{-\ell_{ij}(G)}$, where $\ell_{ij}(G)$ is the length of the shortest path between i and j in the network G (Dangalchev, 2006), and the factor $\frac{2}{n-1}$ is the maximal centrality attained for the center of a star network.

[d] The homogeneous subsidy for each firm i is computed as $e_i^* s^*$, relative to the average homogeneous subsidy $\frac{1}{n} s^* \sum_{j=1}^{n} e_j^*$.

[e] The targeted subsidy for each firm i is computed as $e_i^* s_i^*$, relative to the average targeted subsidy $\frac{1}{n}\sum_{j=1}^{n} e_j^* s_j^*$.

[f] The primary 4-digit SIC code of a firm in the database.

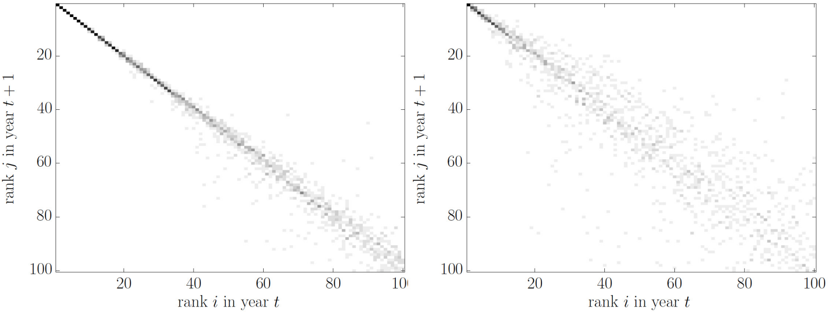

Figure: The transition matrix T_{ij} from the rank i in year t to the rank j in year $t+1$ for the homogeneous subsidies ranking (left panel) and the targeted subsidies ranking (right panel) for the first 100 ranks.

EUREKA Subsidized Firms

Table: Optimal subsidies ranking for the year 2005 including the first 10 firms which also received funding trough EUREKA.

Firm	hom. sub.[%][a]	tar. sub. [%][b]	EUREKA sub. [%][c]	SIC[d]	Country	Rank[e]
Renault	1.4859	0.5354	0.0009	3711	FRA	238
TRW Inc. (ZF Friedrichshafen)	1.1668	0.4041	0.0114	3714	GER	273
Tandberg Data ASA	0.7445	0.3805	0.0019	3572	NOR	283
L'Oreal SA	1.2102	0.1314	0.0023	2844	FRA	405
Sydkraft AB	1.2817	0.1109	0.0004	4911	SWE	432
Carraro Spa.	0.9030	0.0923	0.0022	3714	ITA	458
SDL Inc.	1.0302	0.0144	0.0000	7371	GBR	624
York International Corp.	0.8501	0.0004	0.0001	3585	GBR	774
H Lundbeck A/S	0.8138	0.0000	0.0001	2834	DNK	1088
Riber SA	0.8444	0.0000	0.1728	3679	FRA	1252

[a] The homogeneous subsidy for each firm i is computed as $e_i^* s^*$, relative to the total homogeneous subsidies $\sum_{j=1}^{n} e_j^* s^*$.

[b] The targeted subsidy for each firm i is computed as $e_i^* s_i^*$, relative to the total targeted subsidies $\sum_{j=1}^{n} e_j^* s_j^*$.

[c] The EUREKA subsidies comprise the total accumulated contribution to project costs (relative to the total funds across all firms) in a given year, where all project costs involving a particular firm are considered. For more detailed information see `http://www.eurekanetwork.org/`.

[d] The primary 4-digit SIC code according to Compustat U.S. and Global fundamentals databases.

[e] The rank corresponds to the ranking of 2005.

Summary

- We have developed a model where firms jointly form R&D collaborations (networks) to lower their production costs while competing on the product market.
- We have identified the positive externalities in the network through technology spillovers and the negative externalities of product rivalry from market competition.
- Using a panel of R&D alliances and annual reports, we have tested our theoretical results and showed that the magnitude of the technology spillover effect is much higher than that of the product rivalry effect (i.e. net returns to R&D collaborations are strictly positive).
- Finally, we identified the firms that should be subsidised the most, and we have drawn some policy conclusions about optimal R&D subsidies from the results obtained over different sectors, as well as their temporal variation.